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Development and characterization of a high speed linear-moving-stage for multispectral measurements

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Abstract. Multispectral imaging is one of the key topics in the upcoming years, a lot of measurement tasks can be solved using the additional spectral information. For the separation of these additional information bands plenty technologies were developed in the last decades. All of them have characteristic advantages and disadvantages. One working principle is the use of a filter wheel containing different filters between the image sensor and the lens. The additional element inside the light propagation path as well as the lens imperfections lead to chromatic aberrations. To compensate the resulting focus error some investigation were made. One option is the movement of the image sensor stage to a better focus position. Therefore high precision moving stage with high movement speed are characteristic parameters which have to be considered during the construction. In this paper a linear motor stage paired with two high precision linear bearings were connected together to achieve the demanded requirements. For the evaluation of this new approach, several measurements determining the dynamic as well as the static specifications were made to proof the achieved characteristics and will be shown in the paper. With this approach, a miniaturised precision system inside the multispectral imager a precision repeatability of less than four microns can be achieved.

1. Introduction, state of the art and short system description

Image processing is one of the key technologies for optimisation of industrial processes, the option for 100% quality assurance and a lot of other essential industrial and research topics. One thing that some imaging solutions have in common is the movement of parts inside the light propagating path to sample multidimensional images. A major application for these kind of imaging systems is in the field of multi- and hyperspectral imaging. There is no practical way to capture multispectral images in parallel. For most solutions either the sample or some parts of the imaging system have to be moved. There is one solution that will give a good estimation for parallel multispectral imaging namely, the snapshot imager using a multispectral-filter array. To guarantee a high spatial resolution, a high dynamic range over all spectral channels [1], a high spectral accuracy and a high flexibility, a filter wheel system was developed [2]. With this system a rotating filter wheel moves different metal interference filters in front of a CMOS or CCD sensor and captures one image with each different filter. The additional optical element inside the light path as well as the wavelength dependent chromatic aberration of the lens in front of the imager, lead to blurred defocused images. In [3], a solution to overcome these problem was presented. In [3] additional correction glass plates were placed between the filters and the sensor to compensate the chromatic aberrations. An additional way



to overcome this problem was given in [4]. The aforementioned approach uses a voice coil actuation for the movement of the imaging sensor. An optical sensor delivers a position feedback to a microcontroller which generates the pulse width modulation for the moving stage. The problem in that solution was the positioning speed and the stability of the position. In the new approach, a linear motor with a Hall position sensing and a high speed movement will be presented. The focusing for the different filters is done along the red arrow is showed in figure 3.

2. Moving system stage for multispectral measurements

The moving stage, which consists out of two high precision linear bearings, a high precision linear motor and a special mechanical mounting (figure 1), were integrated in a self-constructed 12-channel-multispectral imager. For the correction of the chromatic aberration [3], the image sensor is mounted on two high precision linear bearings, which will guarantee a deviation of less than one micron along the specified working range of four millimetres. This enables a wide working range for the chromatic error compensation as well as for the usage of a wide variety of different lenses and filters inside the system, while holding the sensor in a stable lateral position to minimise image shifts. The linear motor is directly connected in the middle of these two bearings (see figure 1, centre and right). With the definition of the image coordinate system in the upper left corner of the images, the rows of the image sensor represent the x-direction and the columns the y-direction (figure 1, left). So a better bearing performance along the x-axis will be expected. During the assembly of the system, the linear motor was actuated along the working range while the mounting was not fixed, so the stresses resulting from the mechanical over-determined construction will be reduced, which translates to a decrease of friction along the moving range. The focusing for the different filters is done along the red arrow shown in figure 3. The electronic implementation into the camera system was done using a serial bus to receive new positions and for sending a feedback of the current position from the positioning stage. The internal controller of the moving stage offers the option to implement codes for some macros for some special movement procedures. To adjust the zero position, the moving stage drives the sensor into the end position and observes the slope of the motor current for this position. After the rise of a defined limit, the counter will be set to zero and the current will be switched down. Additionally, a light barrier or a micro switch can be adapted and read out. With some investigations on the current switch method an uncertainty of less than four micrometres, e.g. less than one increment, was achieved. Besides the automatic detection of the zero position, an automatic dynamic calibration can be activated after the restart of the system. The linear motor offers acceleration of 30000mm/s^2 , which leads to very high moving speeds of the image sensor. In the current setup, the moving speed is not the limiting constraint. The moving range in this application can be set with a resolution of 1000 steps with a minimum step size of four micrometres.

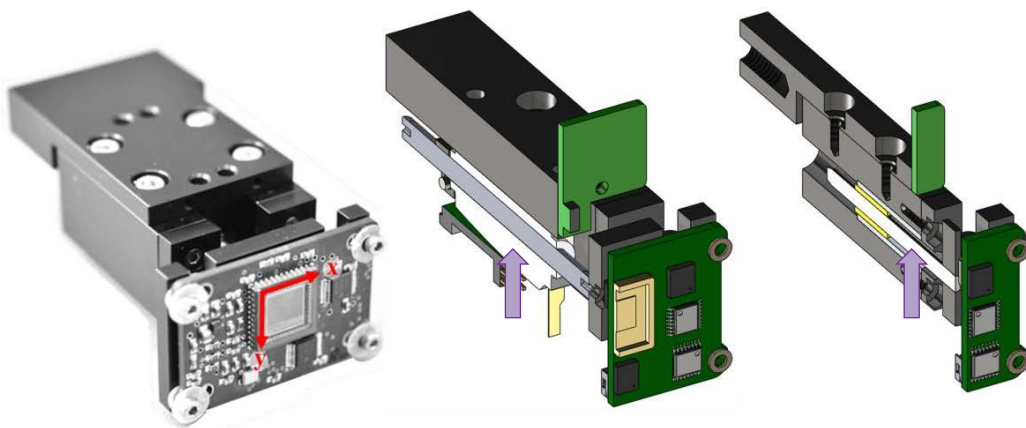


Figure 1: Shows an (left) image of the imaging sensor, its Cartesian coordinates and the moving stage. A sketch shows a cut of the moving stage and its main components with the (centre, purple arrow) linear motor and (right, purple arrow) the linear bearings in evidence.

3. Moving stage investigation static conditions

The first investigations with the new construction were done on an optical coordinate measurement system (OCM) to guarantee high precision results. With the OCM setup, the manufacturer guarantees a maximum permissible error of less than $0.7\mu\text{m}$. For the characterization, the camera system was mounted on the OCM (figure 2). Optical probing between the static parts (connected to the camera housing) and the moving part of the actuator stage was done using an image processing toolset, part of the OCM.

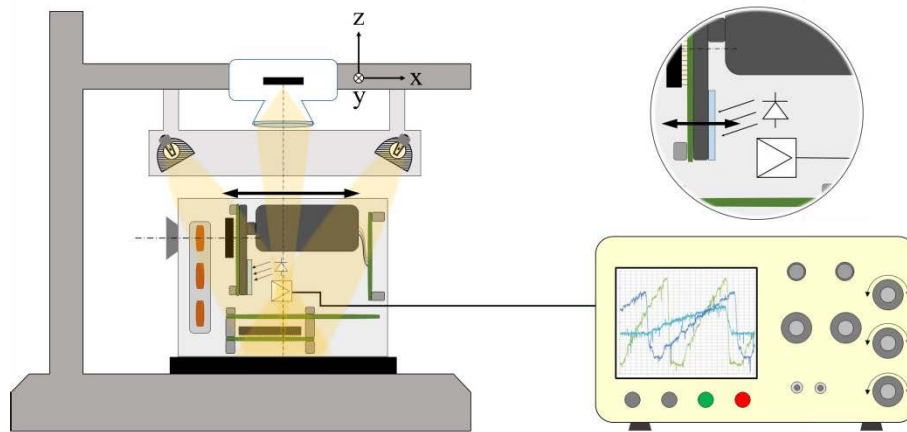


Figure 2: Test setup for dynamic and static investigations on the sensor moving stage.

A typical edge detection algorithm was applied for the displacement measurement. The algorithm is based on 100 search lines, which were placed on both the moving and on the static parts. With this method a high accurate edge detection can be achieved. For the following description of the experiments, “static condition” means that the measurements were done after the positioning. The results in figure 3 display the moving stage characteristics along the working range of four millimeters. The steps for these experiments were set on $200\mu\text{m}$ over the working range of $4000\mu\text{m}$ (1000 counts).

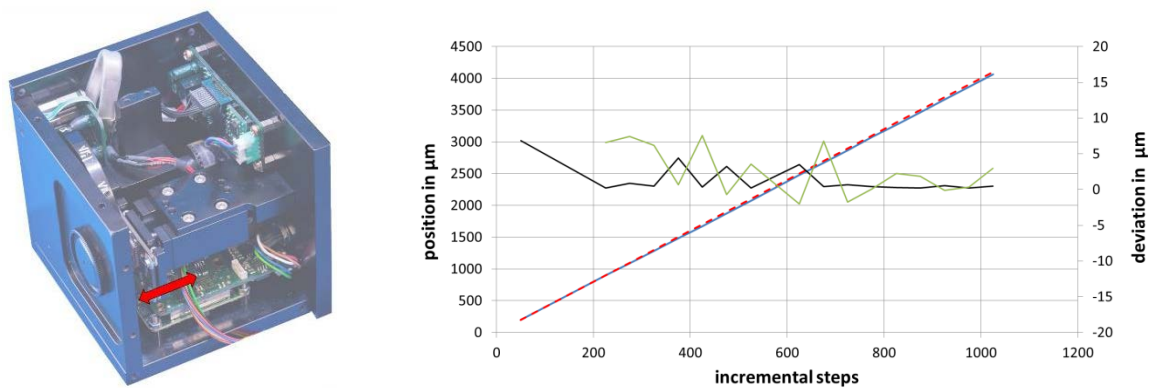


Figure 3: Smart Spectral Imager 2.0 (SSI) with moving image sensor stage (left), moving system characteristics along the working range (10 repetitions), (achieved position (blue), expected position (dashed red), local standard deviation (black), position error at expected position).

The system behavior is nearly linear and therefore can be treated as such. The cumulated error without correction over ten repetitions is $63\mu\text{m}$ at the upper position limit. The repeatability of the selected positions was calculated with less than one micrometre according to table 1. Additional tests for the characterization of the movement error in x and y direction were made outside the OCM. Therefore the SSI was set into typical working conditions with a lens and a circle calibration target. The center point of the circle target was calculated in a similar way to the edge detection method

mentioned previously. The results of the detected center point coordinates are presented at table 1. The deviation along the full range is less than one micrometre, nearly the same conditions as in a three-chip-camera system.

Table 1: static positioning characteristics integrated in the camera system of the moving stage (standard deviation $n=10$) with one zero setting and moving range steps (200 μm) for z

Range	Deviation x	Deviation y	Deviation z
Full scale raw	+/- 1,605 μm	+/- 2,875 μm	+/-0,9 μm
Full scale corrected	+/- 0,405 μm	+/- 0,295 μm	+/-0,9 μm
C-mount position	+/- 0,28 μm	+/- 0,205 μm	+/-0,4 μm

After the first experiments on full working range, the system characterization on short distances was evaluated. To do so, the moving stage was moved on different positions inside the moving range with step sizes of four, twelve and twenty micrometres to get some information about the stick slip characteristics of the system. Up to the movement of three steps (12 μm) nearly nothing will change on the current position. After a movement out of the set position of 50 μm and a following reset on the demanded position, leads to some improvement. With that in mind, the investigation of stick slip characteristics the procedure for moving in small ranges were changed. Therefore three different locations along the working range of the moving stage were chosen (start, middle, end positions). On these positions for the movement of one micrometer, the stage was driven 50 μm out of set position. From this point a new positioning task was started to set the targeted position. For the movement of two increments, 8 μm , this procedure shows no better results in comparison of a direct move. The stability based on the value of uncertainty shows a better bearing condition in the middle of the working range of the moving stage (figure 4).

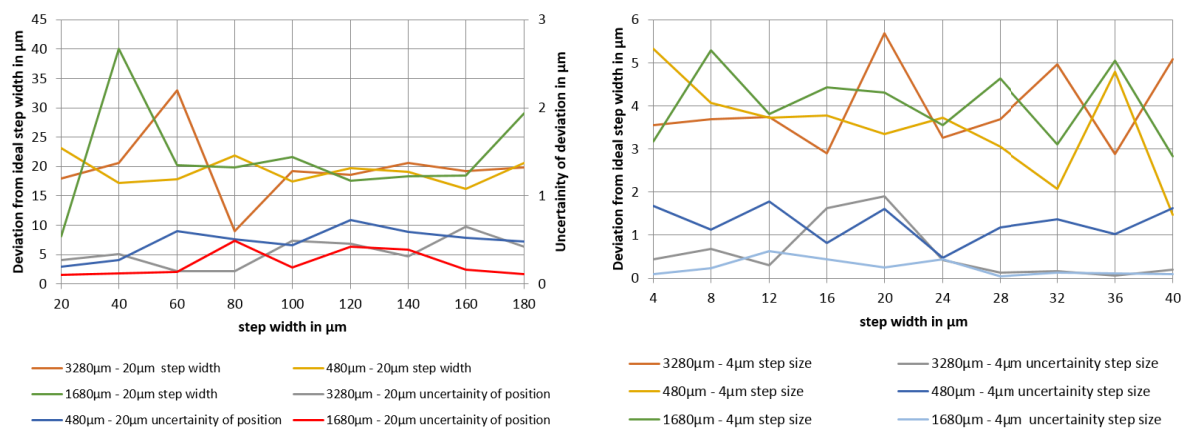


Figure 4: system characteristics in small moving ranges on different positions of the linear bearings.

4. Moving stage investigation dynamic conditions

For the characterisation of the dynamic moving stage parameters, an additional optical distance sensor was adapted in the back of the moving part of the image sensor (showed in details in figure 2, zoomed sketch). The optical sensor was connected to an oscilloscope which samples with a better time resolution than the OCM. The adjustment to the metrological system was realised with a static measurement in the start and end position of the moving program for this test case. So it was possible to evaluate position information with the use of voltage information. The results of these experiments are shown in figure 5. The required timing constraints of 20ms (current sampling speed of the imaging sensor) can be achieved in the incremental positioning mode (figure 5, left). The slightly decrease of the step amplitude versus the position depends on the nonlinear sensor characteristic of the additional optical position sensor and can be ignored.

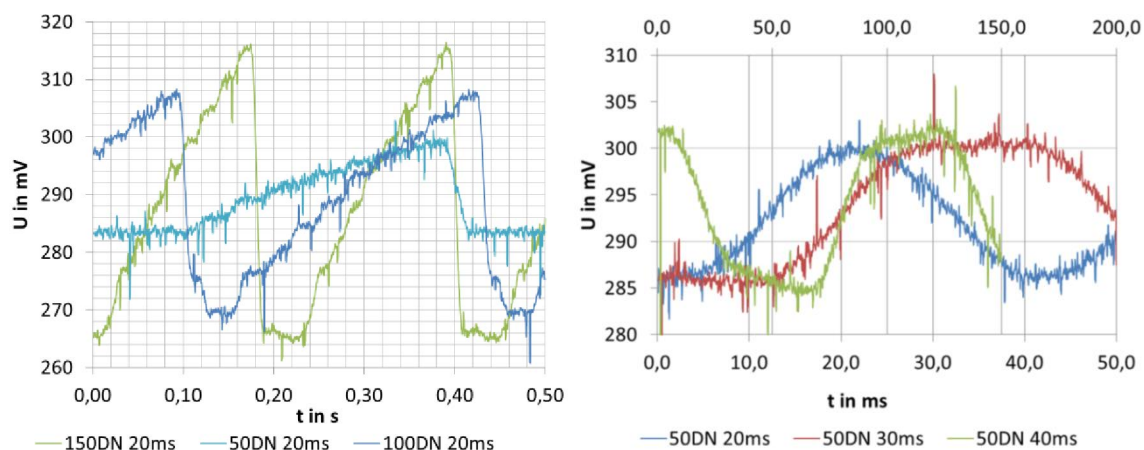


Figure 5: Incremental test mode 20ms settling time (left), ramp mode different settling times (right). DN-digital number equal one increment of four micrometres.

With a distance of 50 DN ($200\mu\text{m}$), the moving stage reaches the dynamic limits. The transition needs roughly 10ms and the set position will be achieved only on the top for roughly 5ms (figure 5, blue line on the right image). In first experiments, the gap (discontinuity) shown in figure 5 and figure 6 will not happen in typical lenses – typically it is less than 100DN range (see figure 6). Some quasi-dynamic experiments were done additionally. For such, the moving stage was moved along the working range with maximum acceleration. On the position $400\mu\text{m}$, $1600\mu\text{m}$, $3200\mu\text{m}$ the stage was stopped and the current position was captured using the OCM - results for ten repetitions the results presented in table 2. Despite of the high requirements measured on this evaluation, the system shows a very good performance with a deviation of less than the specified resolution from manufacturer.

Table 2: quasi static positioning characteristics (n=10)

Position	Position $400\mu\text{m}$	Position $1600\mu\text{m}$	Position $3200\mu\text{m}$
Deviation	$\pm 1,314\mu\text{m}$	$\pm 0,634\mu\text{m}$	$\pm 0,966\mu\text{m}$

5. Moving stage investigations on multispectral filter system

In figure 6, the application of the edge-based auto-focus algorithm for three different lenses with three different fields of view (ranging from 3mm per 3mm to 200mm per 200mm) can be seen.

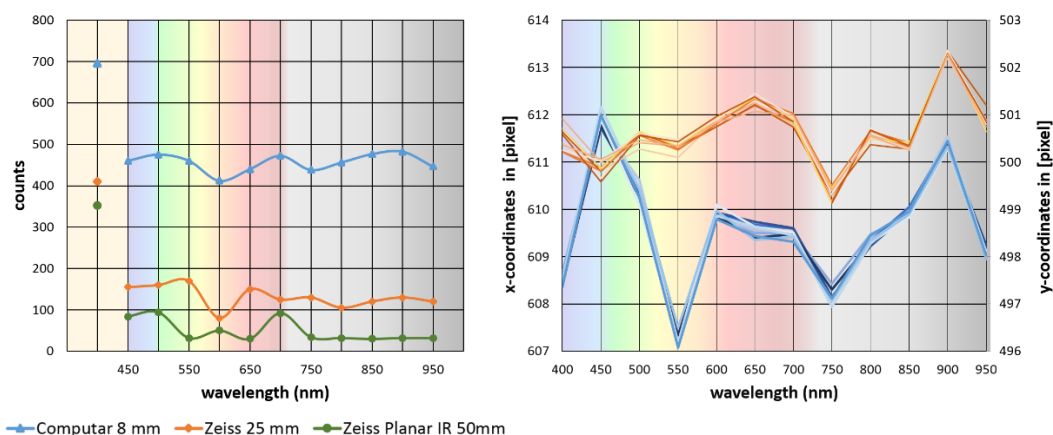


Figure 6: typical lens characteristics of different field of views (left), stability experiment of n=10 repetitions of sensor movement (right) and the influence on image coordinates in x left axis and y right axis.

The yellowish area (left side of the figure 6) shows the focus position for a broad banded light, i.e. illumination with halogen lamps without filtering, where each count corresponds to ca. $4\mu\text{m}$. The

illumination of the sensor with monochromatic light gives on average a difference on focus of ca. 955 μm , 1115 μm and 1210 μm for the Computar 8mm, Zeiss 25mm and Zeiss Planar IR 50mm, respectively, compared to operation without filter. The biggest deviation was found to be at 600nm for the Zeiss 50mm (1320 μm from focus position without filtering). The deviation between values within filtered light (rainbow to grey region in figure 6) is significantly smaller than the values discussed before, showing the following peak to mean value deviations: -10% (-176 μm) for the Computar 8mm lens, -40% (-205 μm) for the Zeiss 25mm (both at 600nm) and +90% (178 μm) for Zeiss Planar IR 50mm at 500nm. This experiment characterizes the chromatic error along the optical path of the objective lens used and highlights the difference between measurements done under broadband light and monochromatic light. Notice that if there were no chromatic error along the optical axis, the curves showed on the right side of the image would be flat and parallel to the abscissa. For this experiment, it was noticed that a resolution of five counts (20 μm) is enough to perform measurements with high quality, not being necessary to go beyond it.

6. Conclusion

The result of the system investigation allows a high precision movement of the image sensor. The resolution of four micrometres (according datasheet) delivered out of the linear motor can be achieved in the moving direction. With the definition of a coordinate system in the middle of the imaging sensor with a positive z direction out of the zero point the moving system, the moving stage reaches less than one micrometre deviation in x and y direction and less than two micrometres in z direction. The working range inside the multispectral imager is four millimetres with a resolution of 1000 increments, in contrast to what was observed in [4]: deviation of 16 μm was achieved over a working range of 1.5 mm, which shows a great improvement from our previous work/system. With this solution, the focus of the multispectral images can be adjusted with a high precision. In respect to the dynamic investigations, dynamic focussing can be done stable with less than 20ms depending on the way that have to be moved. A dynamic limit for stable sensor positioning of 20 $\mu\text{m}/\text{ms}$ can be achieved in this current realization.

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